STRAIN GAUGE

FIELD OF THE INVENTION

The present invention relates to a strain gauge for

5   measuring strain, of particular but by no means exclusive
application in measuring strain in cramped environments.

BACKGROUND OF THE INVENTION

One existing type of strain gauge is the electrical

10   resistance foil strain gauge. For uniaxial strain these
typically require bridge completion and precision
conditioning equipment. Further, electrical resistance
foil strain gauges generally use higher power levels than
is desirable and their use involves careful work by

15   personnel owing to their low output signal levels.

Another broad type of gauge is the "clip" gauge, which
incorporate a full bridge. However, clip gauges generally
do not have a low profile, and are unsuitable for

20   permanent installation. Further, they also consume
considerable power and are relatively expensive.

Columbia Research Laboratories, Inc. produces a full
bridge product using metallic gauges, but this does not

25   have as high a sensitivity as is desirable in many
applications.

Thus, existing strain gauges have relatively high power
requirements, generally require bridge completion, and

30   have low output signal levels.

SUMMARY OF THE INVENTION

The present invention provides, therefore, a strain gauge,
having:

35.   a silicon strain sensing element for sensing
strain with first and second load points and provided with
a pair of piezo-resistors located between said load points

such that, when said strain sensing element is subjected
to tension or compression at said load points, a first of
said pair of piezo-resistors is subjected to compression
and a second of said pair of piezo-resistors is subjected
5   to tension;

          wherein a change in relative resistance of said
pair of piezo-resistors is induced by subjecting said
strain sensing element to compression or tension.

10   Preferably said strain sensing element comprises a curved
silicon member (preferably a ring and more preferably a
circular ring or annulus).

Those skilled in the art will understand that structures
15   other than circular members can be used to generate
compressive and tensile regions in silicon suitable for
measuring using piezo-resistors. For example,
alternatives include ellipses, ovals, one or more curves
with one or more straight portions, and angular members
20   (such as a "V" shape or a zig-zag member).

In one particular embodiment, the strain sensing element
comprises a silicon ring or annulus.

25   The strain sensing element may include two or more load
points and respective sets of piezo-resistors between each
respective pair of load points. For example, the strain
sensing element may comprise a ring with two load points
and two pairs of piezo-resistors.
30
Preferably the strain sensing element comprises a silicon
ring or annulus with a plurality of load points spaced
substantially equidistantly around the perimeter of said
ring or annulus.
35
The strain gauge may include a plurality of strain sensing
elements (such as silicon rings or annuli). Preferably

each of said strain sensing elements include at least one
load point coupled to a load point of another of said
strain sensing elements.

5   In one embodiment, the strain gauge includes a plurality
of strain sensing elements (such as silicon rings or
annuli) arranged linearly, in a ring or other desired
geometry each having a load point coupled to or common
with a load point of any adjacent one or more of said
10   strain sensing elements.

Preferably said gauge includes a detector responsive to
changes in the relative resistance of said pair of piezo-
resistors.
15
Preferably said strain sensing element is provided with
two pairs of piezo-resistors, arranged so as to constitute
a Wheatstone Bridge.

20   In one particular embodiment, the strain sensing element
is provided with a plurality of pairs of piezo-resistors,
arranged so as to constitute a Wheatstone Bridge, and the
gauge includes a current or potential sensitive device
(such as an microammeter or differential amplifier)
25   arranged to respond to changes in the relative resistance
of said piezo-resistors.

The invention also provides a strain gauge incorporating a
strain measuring structure fabricated in silicon to
30   measure strain, comprising:
              the strain measuring structure having a plurality
of connection members adapted to connect the strain
measuring structure to an external structure that in use
transmit the strain in the external structure to the
35   strain measuring structure; and
              a compliant structure connected to the connection
points by two or more tethers, the compliant structure

being configured to translate strain at the connection
points to compressive and tensile strains within the
compliant structure, said compliant structure comprising
piezo-resistors fabricated within the structure for the
5   purpose of detecting compressive and tensile strain in the
compliant structure.

Preferably said piezo-resistors are fabricated in pairs so
that under compressive load one is in compression and one
10   is in tension and under extensive load the one that was in
compression is under tension and the one under tension is
under compression.

Preferably piezo-resistors are arranged electronically to
15   reduce changes in resistance due to thermal effects.

In one embodiment the strain gauge further comprises a
base structure that does not experience strain and other
piezo-resistors fabricated on parts of the base structure
20   and can thus be used as temperature sensors.

Preferably said other piezo-resistors are used in
temperature correction for the piezo-resistors of the
compliant member.
25

The strain gauge may comprise means to apply a bias
voltage between the strain sensitive piezo-resistors of
the compliant member and the substrate or doped well that
they are in order to control response of said strain
30   sensitive piezo-resistors.

The strain gauge may be fabricated with conductive tracks
to the connection points so that material may be electro-
deposited at the connection points to provide a raised
35   point for bonding to an external structure for the
purposes of monitoring the strain in the external
structure.

The strain gauge may comprise a circular silicon structure with two tethers arranged opposite each other and four piezo-resistors arranged in pairs opposite each other and

5 substantially at right angles to the tether points and connected in a Wheatstone bridge configuration so that there is little or no change in the different voltage of the Wheatstone bridge with change in temperature and there is a change in the difference voltage of the Wheatstone

10 bridge when the structure is under strain.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the invention may be more clearly ascertained, embodiments will now be described, by way of

15 example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic view of a uniaxial strain gauge according to a first embodiment of the present invention;

20 Figure 2 is a schematic view of the strain sensing element of the strain gauge of figure 1;

Figure 3 is a schematic circuit diagram of a strain gauge measurement circuit for use with the strain gauge of figure 1;

25 Figure 4 is a plot of change in resistance $\Delta R\,(\Omega)$ as a function of microstrain for a strain gauge constructed according to the embodiment of figures 1 and 2;

Figure 5 is a schematic view of a biaxial strain

30 gauge according to a second embodiment of the present invention;

Figure 6A is a photograph of an elongate strain gauge according to a third embodiment of the present invention; and

35 Figure 6B is a detail of the strain gauge of figure 6A.

DETAILED DESCRIPTION OF THE DRAWINGS

A uniaxial strain gauge according to an embodiment of the
present invention is shown generally at 10 in Figure 1.
The strain gauge 10 comprises a three dimensional,
5   integral machined silicon structure, and includes a
rectangular outer silicon frame 12, within which is a
strain sensing element in the form of silicon annulus 14.
The silicon annulus 14 is attached to two load points 16a,
16b respectively, by means of silicon tethers 18a, 18b at
10 diametrically opposite points on the outer circumference
of annulus 14. These load points 16a, 16b are coupled to
the silicon frame 12 by means of respective pairs of
compliant silicon tethers 20a, 20b. It is by means of
load points 16a, 16b that the gauge 10, in use, is bonded
15 to the structure being monitored for strain.

Herein the term "silicon" is used to refer to the base
material being silicon. Persons skilled in the art will
appreciate that typically the silicon will be "doped" with
20 impurities to improve its ability to carry charge and/or
to vary the properties of different portions of the
silicon.

In this embodiment, the silicon annulus 14 has an outer
25 diameter 10 mm, a thickness 100 μm and width (i.e. the
distance from the inner circumference to the outer
circumference) 100 μm.

The strain sensing element, silicon annulus 14, is thus a
30 free standing mechanical structure for measuring load,
with that free standing structure attached to a larger
frame (viz. silicon frame 12) via compliant tethers 20a,
20b. Fabrication techniques familiar to those skilled in
the art are used to form piezo-resistive elements, metal
35 contacts and any electronic circuitry on the silicon
wafer. In order to produce the free standing structure a
deep etching process, such as deep reactive ion etching,

is used. Those skilled in the art will be familiar with
this process for forming deep structures in silicon that
already has electronic circuitry fabricated on it - e.g.
silicon processing lithography and doping techniques.

5

The strain gauges are fabricated in silicon using
techniques to produce substantially 3 dimensional
structures with walls and substantially parallel sided
cavities that are substantially at right angles to the
10   surface of the silicon. The Bosch (R) deep reactive ion
etching process would be one technique to achieve this.

The structures are constructed in such a way that when
released from the silicon wafer or an underlying carrying
15   wafer or handle wafer the thickness of the released
structures is substantially uniform. One approach to
achieve this would be to use silicon-on-insulator wafers
with the strain gauge structures on the device side (where
the electronics and mechanical structures are formed). The
20   Bosch (R) deep reactive ion etching process stops at the
oxide between the device and the handle side thus defining
the depth of the mechanical structures.

The final stage of fabrication of such devices is the
25   release of the deep machined structures from the silicon
handle layer. This can be performed by complete removal
of the handle silicon, by deep etching the handle silicon
from the back side of the wafer at regions that correspond
to the mechanical structures on the front side of the
30   wafer, or by selective etching of the insulating layer
between the device silicon and the handle silicon in the
regions where the deep mechanical structures are located.
Those skilled in the art will recognize that electrical
circuits fabricated previously may need to be protected
35   during this processing and that there are a number of
suitable techniques for doing this; in any particular
case, the preferred technique will depend on the approach

- 8 -

taken to release the mechanical structures.

Those skilled in the state of the art will realize that
integrated circuits such as current or voltage amplifiers,
5   analog to digital circuits, interface circuits,
communications circuits, micro controller circuits and
other circuits could be incorporated on the silicon during
the processing before the fabrication of the silicon
structure.

10

Figure 2 is a schematic view of the silicon annulus 14.
Annulus 14 is provided with two pairs of identical piezo-
resistors 22a,b 24a,b, located at diametrically opposite
points on one face of the annulus 12. The four piezo-
15   resistors 22a,b 24a,b are fabricated onto the silicon
annulus 14, and are oriented so as to extend parallel to
each other and essentially circumferentially to the
silicon annulus 14. Each pair of piezo-resistors 22a,b or
24a,b includes a first piezo-resistor (22a and 24a
20   respectively) located near the outer circumference of the
silicon annulus 14 and a second piezo-resistor (22b and
24b respectively) located near the inner circumference of
the silicon annulus 14.

25   In broad terms, strain gauge 10 operates as follows. The
strain gauge 10 is bonded to the structure to be measured
for strain at load points 16a, 16b, and is consequently
predominantly in plane with the surface of the structure
on which the strain is to be measured. When the load
30   points are subjected to compression or tension, those
forces are transmitted, via silicon tethers 18a, 18b, to
the silicon annulus 14 at respective diametrically
opposite points 26a, 26b of the outer circumference of the
annulus 14, 90° from the piezo-resistors 22a,b, 24a,b.
35   This induces the silicon annulus 12 to distort into a
marginally elliptical configuration (being either
compressed or stretched at points 26a, 26b); as a result,

the two outer piezo-resistors 22a, 24a will be
respectively either stretched or compressed while the two
inner piezo-resistors 22b, 24b will be, respectively,
compressed or stretched.

Electrical contacts and connections are made individually
to each piezo-resistors 22a,b, 24a,b and taken off the
silicon annulus 14 on the flexible silicon tethers 20a,
20b, which are fabricated on the silicon at the same time
as the annulus 14. The tethers 18,20 are typically 1/3 to
equal to the thickness of the strain sensing element.
Those skilled in the art will realize that a number of
tether geometries are possible and that both the thickness
and total length of the tether are important in
determining the compliance of the tether. Tether length
can be increased in a confined space by using a geometry
that turns back on itself.

Thus, the signals from the piezo-resistors 22a,b, 24a,b
are indicative of the strain experienced by the strain
gauge 10.

Figure 3 is a schematic circuit diagram of a strain gauge
measurement circuit 30 for use with strain gauge 10, with
a schematic representation of the gauge 10 including
piezo-resistors 22a,b, 24a,b. Generally, it will be noted
that the piezo-resistors 22a,b, 24a,b and the circuit 30
together constitute a Wheatstone Bridge. The
piezo-resistors have substantially equal intrinsic
resistances so, when the gauge 10 is under no compression
or tension, the Bridge will be substantially balanced.
However, when the gauge 10 is under compression (or
tension), the outer piezo-resistors 22a, 24a will both be
under tension (or respectively compression) and the inner
piezo-resistors 22b, 24b will both be under compression
(or respectively tension). Consequently, in each pair of
piezo-resistors one (inner or outer) will have increased

resistance while the other of the pair will have decreased
resistance.

The circuit 30 comprises a first power supply 32 for
5   providing the power for the Wheatstone Bridge. First
power supply 32 provides - in this embodiment - a supply
of approximately 3 V, and could be in the form of a 3 V.
battery. It will be understood by those skilled in this
art, however, that the strain gauge 10 could operate with
10 a wide range of voltages, such as from 1 V or less up to
the limit of the Si integrated circuit technology used to
fabricate it.

The circuit includes second power supply 34 (in this case
15 of approximately 0.6 V), connected to substrate pad 36, to
reverse bias the piezo-resistors to wafer (or well)
junction. It will be appreciated that other bias voltages
can be used; in general, this bias is set to be as large
as possible relative to the voltage that is used to do the
20 measurements (see below). Also, in this embodiment the
substrate is positively biased, owing to the particular
doping of the piezo-resistors; with alternative doped
piezo-resistors, the bias may therefore be negative.

25 The bias is provided because the piezo-resistors are doped
silicon in the oppositely doped silicon wafer (or it could
be a specially doped well). Thus, the boundary from a
piezo-resistor to the wafer (or well) thus constitutes a
diode, which is reverse biased so that the current stays
30 in the piezo-resistor.

Second power supply 34 could be, for example, in the form
of a 1.5 V battery with two 100 kΩ resistors connected in
series across it and a resulting centre point (at 0.75 V)
35 used to bias the substrate.

In one alternative arrangement, the substrate of the

strain gauge 10 is connected directly to the positive
terminal of the second power supply 34, although this
might lead in some cases to voltage modulation effects in
the piezo-resistors 22a,b, 24a,b. The extent to which the
5   diode (referred to above) is reverse biased affects the
resistance of the diode owing to depletion of current
carriers. If the diode is just connected to the positive
rail, the voltage drop down of the piezo-resistors will
give a reverse bias. However, as this changes (owing to
10   changes in strain) there may be a secondary affect due to
changed bias and depletion of the current carriers. Thus,
it may be beneficial to have a strong reverse bias to
reduce this effect. Also, changing the reverse bias could
be used as a fine tuning technique, so it is envisaged
15   that the circuit 30 could profitably include a mechanism
for controlling the bias and hence act as a compensation
system.

Between the second power supply 34 and the substrate is
20   optionally located a first resistor R1, to limit current
if the second power supply 34 cannot be current limited.
As there should be very little current, R1 in this
embodiment is approximately 100 kΩ, though the precise
value is not critical. Between first resistor R1 and the
25   substrate is a first ammeter mA1, for checking that there
is not any excess current flowing. Consequently, this
milliammeter should read close to zero.

A second current limiting resistor R2 and a second ammeter
30   mA2 are connected in series between the first power supply
and the first pair of piezo-resistors 22a,b. Resistor R2
is used during set up, and possibly during a first set of
measurements. Resistor R2 has a resistance of
approximately 4.7 kΩ, which limits the current to at most
35   0.6 mA. Resistor R2 could be shorted out for most of the
measurements to ensure a constant excitation voltage.

Second ammeter mA2 monitors the total current through the
Wheatstone Bridge.

Piezo-resistors 22a and 24b and piezo-resistors 22b and
5   24a are connected to respective terminals of a
differential amplifier 36. The differential amplifier 36
thus takes the voltages from the midpoints of the
Wheatstone Bridge. The output of the differential
amplifier 36 is then input into a chart recorder or some
10 other data acquisition system (not shown) that accepts
differential floating inputs. The advantage of the
Wheatstone Bridge is that it relies on the relative
resistance of the two pairs of resistors and hence is
relatively unaffected by changes in absolute resistance
15 (e.g. due to heat) because the piezo-resistors will behave
similarly in response to changed conditions.

Tensile and compressive stresses are distinguishable, as
the potential across differential amplifier 36 when the
20 gauge 10 is under tension will be of opposite polarity to
that when the gauge 10 is under compression.

The resistances used in gauge 10 are of the order of ten
thousand ohms, compared with three hundred and fifty ohms
25 typical of existing devices, which requires significantly
less power. Further, the gauge 10 is preferably formed as
an integral silicon structure, which ensures that each
piezo-resistor experiences the environmental conditions
(including most particularly temperature) and so closely
30 maintain the same relative electrical resistance.

Strain gauge 10 optionally includes additional piezo-
resistors 42a,b and 44a,b of the same characteristics as
piezo-resistors 22a,b and 24a,b in the annulus 14. They
35 are fabricated on the silicon frame 12 so will not be
exposed to the strain that piezo-resistors 22a,b and 24a,b
experience. Piezo-resistors 42a,b and 44a,b can thus be

used as controls to compensate for thermal affects.

It will be understood that the measurement circuit 30, as
well as the circuitry that processes the outputs of
5   circuit 30 (together with any other desired integrated
circuit functions), can be included on the strain gauge
10. Further, the gauge 10 is preferably formed from the
same material (i.e. silicon wafer) as used for
implementing signal conditioning.
10
The gauge 10 can be bonded to the surface of the structure
being tested at two (or, in other embodiments, more)
points. The load path (or paths) connecting these points
do not take the most direct path (thus (a) reducing
15   stiffness to minimise attachment stress, and (b)
separating the stress into in phase and antiphase
components).

Further, strain gauge 10 should provide a higher level of
20   compliance than existing devices, which is of particular
importance when attached to steel.

In order to facilitate the bonding of the load points to
the structure to be monitored, an electrical connection
25   can be run to exposed conducting structures on the load
point pads so that material (for example, metal) can be
electro-deposited onto the load point pad (for example, by
electroplating a metal). This permits, advantageously,
the in-situ fabrication of load points that are slightly
30   proud of the surface of the sensor and silicon frame to
make it easier to attached the load points to the surface
being monitored and not inadvertently come into contact
with other parts of the structure. A strain gauge with
such load point pads can be potted in a compliant polymer,
35   leaving the faces of the load point pads exposed so that
the whole device could bonded to the surface of a
structure while ensuring that the load is transmitted

- 14 -

substantially into the load point pads and to the load
points on the strain sensors.

In addition, the entire silicon wafer can be processed to
5   electro-deposit pads on the load points. It will be
understood by those skilled in the art that it is
desirable (though not essential) to fabricate the
electronics to control this process on the wafer itself;
doing so is expected to afford more uniform results for
10   all of the devices across the wafer.

EXAMPLE
A strain gauge was constructed according to the embodiment
of figures 1 and 2, and tested with a circuit comparable
15   to that of figure 3. Zero strain resistance was
approximately 10 kΩ, and total excitation current 200 μA
(100 μA per arm of the bridge). This corresponds to
approximately 2 V excitation voltage. Thus, the total
power in the example was 400 μW or 100 μW per resistor.
20

Figure 4 is a plot of change in resistance $\Delta R(\Omega)$ as a
function of microstrain. The microstrain increased from
zero to approximately 3890 and then decreased back to
zero. Thus, there are two curves in the plot for each of
25   the four piezo-resisters, which have been labelled in
accordance with figures 2 and 3. The resistance increases
for two piezo-resistors (22b, 24b) and decreases for the
other two piezo-resistors (22a, 24a) because the former
two were placed under tension and latter two under
30   compression.

It should be noted that the effective gauge factor for a
single piezo-resistor in the silicon annulus is lower than
the gauge factor that one would obtain if the
35   piezo-resistor were exposed in isolation to the same
strain. That is, the piezo-resistors do not see the
entire strain that is applied at the load points of the

silicon ring. This is due to the geometry of the gauge
and the use of thin tethers to attach the strain sensing
element to the rest of the silicon structure, which
increases compliance but reduces strain at the measurement
5   points, viz. the locations of the piezo-resistors. For a
ΔR of 100 Ω, the strain was found to be approximately 3000
microstrain, hence:

$$(\Delta R/R_0)/(\Delta L/L_0) = (100/10000)/0.003 = 3.3.$$

10
This is not much greater than a standard metal foil strain
gauge. A change in resistance of 100 Ω corresponds to a
voltage change of around 0.01 V for a single piezo-
resistor at around 3000 microstrain. A standard 120 Ω
15   metal foil strain gauge with a gauge factor of 2 gives a
resistance change of around 120 × 2 × 3000 × 1/1000000 =
0.72 Ω. To obtain the same voltage change for a standard
metal foil gauge as is obtained with the piezo-resistors
requires a current of about 14 mA and thus an excitation
20   voltage of around 1.7 V. The power in a single metal foil
gauge would thus be around 23 mW, which is about 230 times
higher than the piezo-resistors in this embodiment. By a
similar calculation a 350 Ω metal foil strain gauge would
require around 80 times the power.

25
Fabrication of the strain sensitive elements is not
restricted to the configuration of figure 2, viz. with
pairs of elements diagonally opposite each other so that
the gauge is uniaxial. Figure 5 is a schematic view of a
30   strain sensing element in the form of silicon annulus 46
according to a second embodiment of the present invention;
silicon annulus 46 has three equally spaced pairs of
piezo-resistors 48a,b, 50a,b and 52a,b and three load
points 54a,b,c. Each load point 54a,b,c is located
35   between a respective pair of piezo-resistors pairs.

Silicon annulus 46 forms the strain sensing element of a

strain gauge otherwise comparable to that shown in figure
1.

In this embodiment, the three groups of paired piezo-
5   resistors 48a,b, 50a,b and 52a,b make the silicon annulus
46 sensitive to biaxial strains. In a further
alternative, three groups of four (rather than two) piezo-
resistors could be located around the silicon annulus 46,
possibly configured as a bridge. Other configurations
10   such as three half bridges are possible or configurations
with still different numbers of piezo-resistors.

Figure 6A is a photograph of a strain gauge 60 according
to yet another embodiment of the present invention, which
15   includes a silicon frame 62 that provides a base structure
and a series of eight silicon annuli 64 connected in an
essentially linear fashion (and vertically in this view)
by means of rectangular junctions. Gauge 60 thus
comprises an extended gauge with load points along the
20   length of the gauge, viz. at the junctions.

The uppermost (in this view) junction 66 forms a part of
the silicon frame 62, while the lowermost junction 68 (in
this view) is connected to two groups 70a,70b of three
25   thin, flexible silicon strips extending horizontally (in
this view) from lowermost junction 68. Each of the two
groups of silicon strips meets, at its end remote from
junction 68, a respective silicon arm 72a,72b that runs
first vertically (in this view), then doubles back and
30   downwardly to meet a respective further group 74a,74b of
three silicon strips that extend (in this view)
horizontally back to the silicon frame 62 at respective
points 75a,75b. All of the annuli 64, their load points
at the junctions (such as uppermost junction 66 and
35   lowermost junction 68), groups of silicon strips 70a,70b
and 74a,74b and silicon arms 72a,72b are situated in a
machined well in the silicon frame 62 and have been

released from the underlying silicon so that are free to move other than by being constrained at the uppermost junction 66 and at points 75a,b (viz. where the further groups 74a,74b each of three silicon strips meet the

5   silicon frame 62). The machined well is fabricated at the same time as the annuli 64, the junctions/load points (tethers) and a selective etching process is subsequently used to release the structures from the bottom of the well.

10

Along the left and rights sides of the silicon frame 62 are respective pairs of pads 76a,b that form contacts to the silicon frame 62, which are used for applying the bias voltage.

15

Above these are, again on each side, four pads 78a,b which are where connections to the piezo-resistors are made.

The silicon frame 62 also has thin lines 80a,b from the

20   frame's left and right sides (respectively) are where a voltage can be applied to electro-deposit metal or other electro-depositable substance (such as for electroplating) onto the load points so that bumps can be made proud of the silicon surface for attaching the load points to the

25   structure to be monitored.

In addition, strain gauge 60 includes a row of twelve connected resistors 82 at the lower periphery (as seen in this view) of the silicon frame 62, to act as reference

30   resistors.

Figure 6B is a detail of the strain gauge 60, showing one of the silicon annuli 64 with adjacent junctions 84a,84b. It will be seen that each annulus in fact comprises two

35   semi-annuli 86a,86b that are both joined and separated by the adjacent junctions 84a,84b. Each semi-annulus 86a,86b is provided with a set of piezo-resistors 88a,88b.

Modifications within the scope of the invention may be
readily effected by those skilled in the art. It is to be
understood, therefore, that this invention is not limited
5   to the particular embodiments described by way of example
hereinabove. For example, depending on the application,
the number of piezo-resistors between load points may be
varied.

10 Further, any reference herein to prior art is not intended
to imply that such prior art forms or formed a part of the
common general knowledge.